

Recent Results from BaBar, Belle, BESIII and CDF

Stephen Lars Olsen

Department of Physics & Astronomy, Seoul National University, Seoul 151-747, KOREA

Abstract. A brief report of some recent experimental developments concerning the X , Y and Z charmoniumlike mesons states and other puzzling states from the BaBar, Belle, BESIII and CDF experiments is presented.

Keywords: XYZ mesons; BaBar; Belle; BESIII; CDF

PACS: 14.40.Gx, 12.39.Mk, 13.20.He

INTRODUCTION

The XYZ-mesons are an assortment of meson resonances discovered by BaBar, Belle, BESIII and CDF – somewhat haphazardly named X , Y or Z – that have defied assignments to the quark-antiquark $q\bar{q}$ meson structure specified by the classical quark-parton model (QPM). Most of them are seen to have decays to final states with a charmed-quark anticharmed-quark ($c\bar{c}$) pair, which almost certainly means that they have a $c\bar{c}$ pair among its constituents. However, the spectrum of particles that are comprised of only a $c\bar{c}$ pair – the so-called charmonium mesons – is very well understood, the number of unassigned levels is small and the properties of whatever fill them are tightly constrained. It is now generally agreed that at least some of the newly discovered XYZ mesons have a more complex substructure than the $q\bar{q}$ mesons of the QPM. What, in fact, this more complex structure may be remains an open question. One peculiar feature that may be a clue to their ultimate understanding, is that many of these new states have partial decay widths for hadronic transitions to standard charmonium meson states – such as the J/ψ , the ψ' and the χ_{c1} – that are much larger than is typical for the established $c\bar{c}$ mesons.

Other unusual states have been reported. BESII found a large enhancement in the $p\bar{p}$ invariant mass spectrum right at the $M(p\bar{p}) = 2m_p$ mass threshold in radiative $J/\psi \rightarrow \gamma p\bar{p}$ decays. And the Belle group found a huge $\pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2$ & 3) peak in the $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$ cross-section around 10.9 GeV. It is not known if either of these are related to the XYZ mesons.

Although some of these phenomena have been around for a number of years their origins have still not been identified. This remains an experimentally driven subject and the hope is that with enough information, the puzzle (puzzles?) can be solved. In this talk I briefly review some recent experimental results that may have some relevance to their interpretation.

THE $X(3872)$

The $X(3872)$ was discovered by Belle in 2003 as a narrow peak in the $\pi^+\pi^-J/\psi$ invariant mass distribution from $B^+ \rightarrow K^+\pi^+\pi^-J/\psi$ decays [1, 2]. This peak was subsequently confirmed by CDF [3], D0 [4] and BaBar [5]. CDF and D0 see $X(3872)$ produced promptly in inclusive $p\bar{p}$ collisions as well as in B meson decays. In all of the experiments, the invariant mass distribution of the dipion system is consistent with originating from $\rho \rightarrow \pi^+\pi^-$ [6], indicating that the C -parity of the $X(3872)$ is $C = +1$. Charmonium states are all isospin singlets; the decay charmonium $\rightarrow \rho J/\psi$ violates isospin and should be strongly suppressed. A study of angular correlations among the $\pi^+\pi^-J/\psi$ final state particles by CDF led to the conclusion that the only likely J^{PC} assignments for the $X(3872)$ are 1^{++} and 2^{-+} [7].

The unfilled charmonium state near 3872 MeV with $J^{PC} = 1^{++}$ is the 2^3P_1 (χ'_{c1}). However, charmonium models predict this state to have a mass of $\simeq 3905$ MeV, much higher than the world average $X(3872)$ mass, $M_{X(3872)} = 3871.56 \pm 0.22$ MeV [8]. The predicted mass is tightly constrained by the fact that the multiplet partner state, the χ'_{c2} has been found and its mass measured to be 3929 ± 6 MeV [9]. The unfilled $c\bar{c}$ state near 3872 MeV with 2^{-+} is the 1^1D_2 (η_{c2}) state. However, the model prediction for the mass, $\simeq 3837$ MeV, is too low, a prediction that is also tightly constrained, this time by the measured mass of the well established $\psi(3770)$ [8] multiplet partner state.

A striking feature of the $X(3872)$ is that its mass is equal within rather small errors to the $D^0\bar{D}^{*0}$ mass threshold, $m_{D^0} + m_{D^{*0}} = 3871.79 \pm 0.30$ MeV, and this has prompted speculation that it is a molecule-like $D^0\bar{D}^{*0}$ bound state [10]. Deuteron-like interactions between D^0 and \bar{D}^{*0} mesons were studied by Törnqvist in 1994, and he predicted bound states for for J^{PC} values of 0^{-+} and 1^{++} [11]. Now there is a growing consensus that the $X(3872)$ is a 1^{++} $D^0\bar{D}^{*0}$ bound state with some admixture of the χ'_{c1} . The χ'_{c1} component is supposed to

be responsible for its prompt production in $p\bar{p}$ collisions and its decay transitions to charmonium states.

Radiative transitions of the $X(3872)$

Important diagnostics for distinguishing between various possibilities are radiative $X(3872) \rightarrow \gamma\psi'$ and $\gamma J/\psi$ decays. If the $X(3872)$ is the χ'_{c1} or if it is a mixed state where the χ'_{c1} component is primarily responsible for its inter-charmonium transitions, one can expect its partial width for $X(3872) \rightarrow \gamma\psi'$, for which there is good wave function overlap, to be substantially larger than that for $X(3872) \rightarrow \gamma J/\psi$, which are hindered by the poor match of the initial & final-state radial wave functions. A potential model calculation indicates that the $\gamma\psi'$ transition is favored by more than a factor of ten [12]. For the $X(3872) = \eta_{c2}$ case, the situation is reversed and the $\gamma J/\psi$ mode is favored by an order-of-magnitude [13].

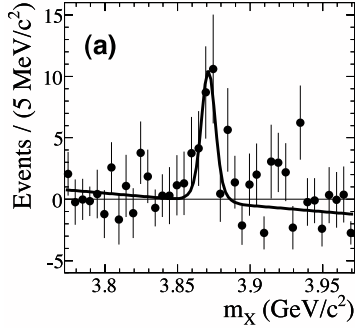


FIGURE 1. The $\gamma\psi'$ invariant mass distribution near 3872 MeV for $B^+ \rightarrow K^+\gamma\psi'$ decays from BaBar. Note that this distribution is background subtracted.

In 2009, BaBar reported $> 3\sigma$ significance signals for $X(3872)$ decays to both $\gamma J/\psi$ and $\gamma\psi'$ [14], (see Fig. 1) with the $\gamma\psi'$ decay mode favored over the $\gamma J/\psi$ transition by a factor of 3.4 ± 1.4 . This year Belle reported preliminary results that claim a $> 5\sigma$ signal for $X(3872) \rightarrow \gamma J/\psi$ at a rate that agrees with BaBar but saw no evidence for $X(3872) \rightarrow \gamma\psi'$ (see Fig. 2). Belle set a 90% CL upper limit on the $\gamma\psi'/\gamma J/\psi$ ratio of < 2.1 , below the BaBar central value [15]. In any case, the large preference for $\gamma\psi'$ compared to $\gamma J/\psi$ that is expected for the χ'_{c1} is not seen.

$$X(3872) \rightarrow \omega J/\psi$$

In 2005, Belle reported a near-threshold $\omega J/\psi$ mass peak in the decay $B \rightarrow K\omega J/\psi$ that they called the $Y(3940)$ [16]. The $Y(3940)$ mass is well above open-charm mass thresholds for decays to $D\bar{D}$ or $D^*\bar{D}$ final states, but was discovered via its decay to the hid-

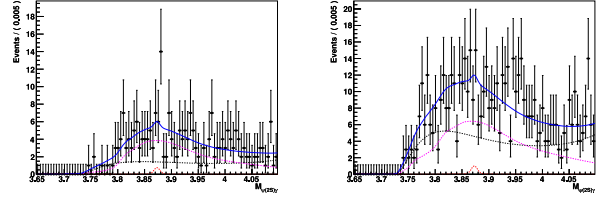


FIGURE 2. The $\gamma\psi'$ invariant mass distribution near 3872 MeV for $B^+ \rightarrow K^+\gamma\psi'$ decays from Belle. The left-side panel shows results from the sample where $\psi' \rightarrow \ell^+\ell^-$, the right-hand shows the results when $\psi' \rightarrow \pi^+\pi^-J/\psi$.

den charm $\omega J/\psi$ final state. A search for $Y(3940) \rightarrow D^*\bar{D}$ decays resulted in a 90% CL lower limit on the ratio $\mathcal{B}(Y(3940) \rightarrow \omega J/\psi)/\mathcal{B}(Y(3940) \rightarrow D^0\bar{D}^{*0}) > 0.71$ [17]. This implies an $\omega J/\psi$ partial width that is much larger than expectations for charmonium. The $Y(3940)$ sighting in $B \rightarrow K\omega J/\psi$ decays was confirmed by Babar in 2008 [18]. Recently Belle reported a near-threshold $\omega J/\psi$ mass peak in the untagged two-photon process $\gamma\gamma \rightarrow \omega J/\psi$ with resonance parameters $M = 3915 \pm 4$ MeV and $\Gamma = 17 \pm 11$ MeV, which are consistent with those of the $Y(3940)$ (see Fig. 3) [19]. If this is the $Y(3940)$, it narrows the J^{PC} quantum numbers down to 0^{++} or 2^{++} . Belle measures $M = 3915 \pm 4$ MeV and $\Gamma = 17 \pm 11$ MeV $\Gamma_{\gamma\gamma}\mathcal{B}(Y \rightarrow \omega J/\psi) = 61 \pm 19$ eV (for $J^P = 0^+$). If $\Gamma_{\gamma\gamma} \sim \mathcal{O}(1$ keV), a value typical for charmonium mesons, then $\Gamma(Y \rightarrow \omega J/\psi) \sim \mathcal{O}(1$ MeV), which is very large for a hadronic inter-charmonium transition.

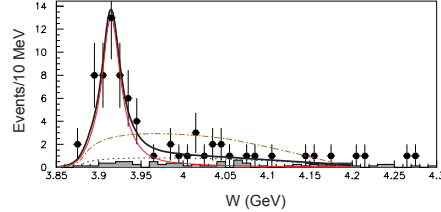


FIGURE 3. The CM energy distribution for $\gamma\gamma \rightarrow \omega J/\psi$ from Belle.

Although the $X(3872)$ mass is below the threshold for $X(3872) \rightarrow \omega J/\psi$ decays, Swanson proposed a composite model in which the $X(3872)$ has a large $\omega J/\psi$ component and that $\omega J/\psi$ decays to the low-mass tail of the ω would be comparable in rate to $\pi^+\pi^-J/\psi$ decays [20]. Belle, in a 2005 unpublished paper, reported evidence for subthreshold $\omega J/\psi$ decays at a rate comparable to that for $\pi^+\pi^-J/\psi$, consistent with the Swanson prediction [21]. This year, the BaBar group reported evidence for $X(3872) \rightarrow \omega J/\psi$ [22] at a rate consistent with that reported by Belle and the Swanson prediction.

A BaBar fit to the $\pi^+\pi^-\pi^0$ lineshape for the selected $X(3872) \rightarrow \omega J/\psi$ events that assumed an odd parity for the $X(3872)$ had a better χ^2 value than a fit that asu-

umed even parity: $\chi^2/d.o.f. = 3.53/5$ for odd parity as opposed to $\chi^2/d.o.f. = 10.17/5$ for even parity. While the statistical significance of this difference is not overwhelming (less than 2σ), it has led to some reconsideration of the 2^{-+} assignment [23].

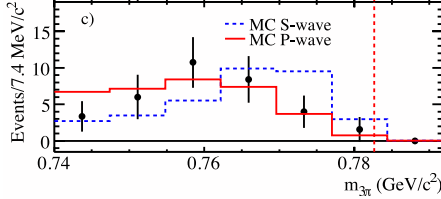


FIGURE 4. BaBar's $\pi^+\pi^-\pi^0$ invariant mass distribution for $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$ decays. The solid (dashed) histogram shows results from an odd (even) parity fit.

RECENTLY REPORTED $\phi J/\psi$ PEAKS

In 2009, CDF reported a narrow 14 ± 5 event near-threshold peak in the $M(\phi J/\psi)$ distribution from $B \rightarrow K\phi J/\psi$ decays [24]. This summer, they reported an update with about twice the data where the excess has grown to a 19 ± 6 signal with a 5.9σ statistical significance (see Fig. 5). The mass and width from the larger sample, $M = 4144 \pm 3$ MeV and $\Gamma = 15_{-6}^{+10}$ MeV, agree well with previous results [25]. They also report hints of a higher mass peak at $\simeq 4275$ MeV but with marginal significance. The mass of the $Y(4140)$ is well above all open-charm thresholds and, thus, such a narrow peak with a strong $\phi J/\psi$ component is not expected for an ordinary $c\bar{c}$ meson. The similarities between the $Y(3940) \rightarrow \omega J/\psi$ seen by Belle & BaBar and the CDF group's $Y(4140) \rightarrow \phi J/\psi$ suggests that they may originate from related sources [26].

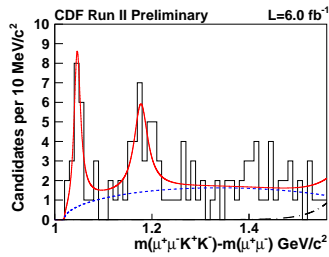


FIGURE 5. The $M(\phi\ell^+\ell^-) - M(\ell^+\ell^-)$ distribution for $B^+ \rightarrow K^+\phi\ell^+\ell^-$ decays where $M(\ell^+\ell^-)$ is in the J/ψ region from CDF. The peak at threshold is the $Y(4140)$, the second peak is at a mass of $\simeq 4275$ MeV.

At the B -factories, the B mesons are produced nearly at rest. Thus, in the process $B \rightarrow KY(4140)$, $Y(4140) \rightarrow \phi J/\psi$ the kaons from $\phi \rightarrow K^+K^-$ have very low momentum and a very small detection efficiency. As a result, neither Belle nor BaBar have been able to either confirm

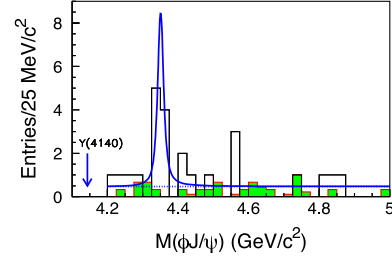


FIGURE 6. The $X(4350)$ peak in the $M(\phi J/\psi)$ distribution for $\gamma\gamma \rightarrow \phi J/\psi$ events from Belle.

or contradict the CDF observation. On the other hand, Belle studied $\phi J/\psi$ systems produced via $\gamma\gamma \rightarrow \phi J/\psi$. They did not see the $Y(4140)$, but did see evidence (with 3.8σ statistical significance) for a narrow peak that they dubbed the $X(4350)$ with mass 4350 ± 5 MeV and width $\Gamma = 13_{-9}^{+18}$ MeV [27] (see Fig. 6). An interesting spectroscopy in the $\phi J/\psi$ channel seems to be emerging.

THRESHOLD $M(p\bar{p})$ PEAK IN $J/\psi \rightarrow \gamma p\bar{p}$

In 2003, BESII reported the observation of a striking enhancement in the $M(p\bar{p})$ distribution in radiative $J/\psi \rightarrow \gamma p\bar{p}$ decays [28]. The result of a fit to a Breit Wigner shape was a peak mass of 1859_{-10}^{+3} MeV, about 18 MeV below the $M(p\bar{p}) = 2m_p$ mass threshold, and a width $\Gamma < 30$ MeV (90% CL). These parameters do not match those of any known resonance. Similar enhancements are not seen in ψ' or $Y \rightarrow \gamma p\bar{p}$ or $J/\psi \rightarrow \omega p\bar{p}$ and the enhancement cannot be fit with $p\bar{p}$ final state interactions.

Ding and Yan suggested that this might be a bound $p\bar{p}$ state (baryonium) in which case it might also be seen to decay to $\pi^+\pi^-\eta'$ [29]. In a study of $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$, BESII found a $\pi^+\pi^-\eta'$ mass peak at 1834 ± 7 MeV with width $\Gamma = 68 \pm 21$ MeV (the $X(1835)$) [30]. It is not clear if the $X(1835)$ is related to the $p\bar{p}$ peak.

An early task at the BESIII experiment has been the confirmation of the above-mentioned observations. Figure 7 shows the $M(p\bar{p})$ distribution from $J/\psi \rightarrow \gamma p\bar{p}$ decays for J/ψ s produced via $\psi' \rightarrow \pi^+\pi^- J/\psi$ decays in a 108M ψ' event sample [31]. The threshold enhancement is evident; a fit gives $M = 1861_{-13}^{+6}$ MeV and $\Gamma < 38$ MeV, consistent with the BESII results.

BESIII also studied the $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ process with a 226M J/ψ event sample. The resulting $M(\pi^+\pi^-\eta')$ distribution is shown in Fig. 8. In addition to a prominent $X(1835)$ signal, two other peaks are evident at higher masses, as well as a large $\eta_c \rightarrow \pi^+\pi^-\eta'$ signal near 3.0 GeV. Preliminary BESIII results for the mass and width for the $X(1835)$ were reported this summer: $M = 1836.5 \pm 3.0(\text{stat})_{-2.1}^{+5.6}(\text{syst})$ MeV and $\Gamma = 190 \pm$

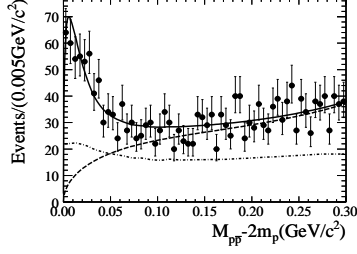


FIGURE 7. The $p\bar{p}$ invariant mass distribution for $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \gamma p\bar{p}$ events from BESIII.

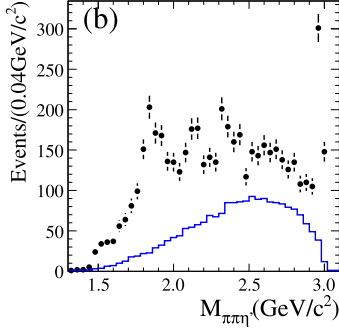


FIGURE 8. The $\pi^+\pi^-\eta'$ invariant mass distribution for $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ events from BESIII.

$9^{+31}_{-36}(\text{syst}) \text{ MeV}$ [32]. The mass agrees well with the BESII result while the width is considerably broader. The BESIII results confirm those from BESII, but the discrepancy between the width values for the $p\bar{p}$ and $\pi^+\pi^-\eta'$ peaks has increased, making it less likely that the two structures are related. The $X(1835)$ and its higher mass partners may be excitations of the η' .

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))$ AT 10.9 GEV

Perhaps the most mysterious of the XYZ mesons are the $1^{--} Y(4260) \rightarrow \pi^+\pi^-J/\psi$, $Y(4350) \rightarrow \pi^+\pi^-\psi'$ and $Y(4660) \rightarrow \pi^+\pi^-\psi'$, first found by BaBar [33, 34] and confirmed by Belle [35, 36] in the initial-state-radiation process $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi(\psi')$. These states have much larger partial widths to $\pi^+\pi^-J/\psi$ ($\pi^+\pi^-\psi'$) than those for $\psi' \rightarrow \pi^+\pi^-J/\psi$ ($102 \pm 3 \text{ keV}$) or $\psi(3770) \rightarrow \pi^+\pi^-J/\psi$ ($53 \pm 7 \text{ keV}$). In fact, the $Y(4260)$ mass coincides with a dip in the $e^+e^- \rightarrow \text{hadrons}$ total cross section [37] and it has a full width of $95 \pm 14 \text{ MeV}$ [8]. This implies a *lower* limit on its $\pi^+\pi^-J/\psi$ partial width of $\sim 1 \text{ MeV}$ [38]. (Since no other decay modes have yet been identified, the $\pi^+\pi^-J/\psi$ partial width may be much larger.) This motivated the Belle experiment to look for similar phenomena in the b -quark sector [39].

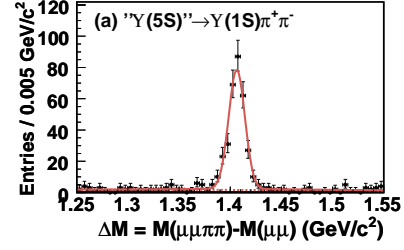


FIGURE 9. The $M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$ distribution for $\Upsilon(5S) \rightarrow \pi^+\pi^-\mu^+\mu^-$ events with $M(\mu^+\mu^-)$ in the $\Upsilon(1S)$ mass range from Belle.

Using their huge sample of 464 million $\Upsilon(4S)$ decays (accumulated for making measurements of CP violation in B meson decays), Belle detected 113 ± 16 events of the type $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ ($\Upsilon(1S) \rightarrow \mu^+\mu^-$), from which it determined the partial width to be $\Gamma(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = 3.65 \pm 0.95 \text{ keV}$ [40], in agreement with expectations for bottomonium mesons. In 2008, Belle accumulated a much smaller sample of 6.5 million $\Upsilon(5S)$ for pilot studies of B_s decays. According to standard bottomonium expectations normalized by the $\Upsilon(4S)$ measurements, this small sample of events should contain at most one or two $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ events. Instead, Belle observed the distinct 325 ± 20 event signal shown in Fig.9. A similarly distinct 186 ± 15 event signal was seen for $''\Upsilon(5S)'' \rightarrow \pi^+\pi^-\Upsilon(2S)$. (I use inverted commas to emphasize that it is not known that the $\Upsilon(5S)$ is in fact the source for these events.) Assuming these signals are from the $\Upsilon(5S)$, Belle infers partial widths of $590 \pm 10 \text{ keV}$ and $850 \pm 18 \text{ keV}$ for the $\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(2S)$ transitions, respectively, both of which are more than 100 times expectations [41].

An important question is whether or not the source of these anomalous $\pi^+\pi^-\Upsilon(nS)$ events is the $\Upsilon(5S)$, enhanced by some dynamical process, or if they are they from a b -quark sector equivalent to the $Y(4260)$. Meng and Chao explored the former approach and proposed a model that attributed the anomalous $\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(2S)$ production rates at the $\Upsilon(5S)$ to rescattering processes of the type $\Upsilon(5S) \rightarrow B^{(*)}\bar{B}^{(*)} \rightarrow f\Upsilon(nS)$, where f denotes scalar $\pi^+\pi^-$ resonances such as the σ , the $f_0(980)$ and/or the $f_0(1370)$ [42]. However, their approach has some problems. First, in their model about two thirds of the contribution to the $\pi^+\pi^-\Upsilon(1S)$ channel is due to the $f_0(980)$. However, the measured $M(\pi^+\pi^-)$ spectrum for this process from ref. [41], shown in Fig. 10, shows no sign of a significant $f_0(980)$ contribution.

A second difficulty with the model can be seen in Fig. 11, also from ref. [41], where the data points show the $\cos\theta_{\text{Hel}}$ distribution for the $\pi^+\pi^-$ system in the $''\Upsilon(5S)'' \rightarrow \pi^+\pi^-\Upsilon(2S)$ events, where θ_{Hel} is the angle

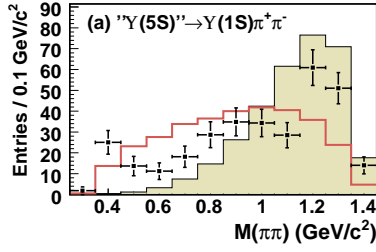


FIGURE 10. The $M(\pi^+\pi^-)$ distribution for the " $\Upsilon(5S)$ " $\rightarrow \pi^+\pi^-\Upsilon(1S)$ events from Belle.

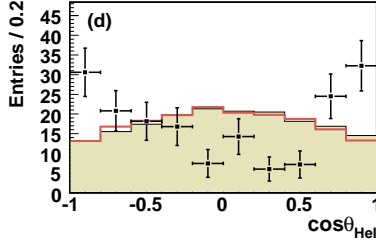


FIGURE 11. The $\cos \theta_{\text{Hel}}$ distribution for the " $\Upsilon(5S)$ " $\rightarrow \pi^+\pi^-\Upsilon(2S)$ events from Belle.

between the π^+ and the $\pi^+\pi^-$ system boost direction in the $\pi^+\pi^-$ CM. Here large and significant deviations from an acceptance-weighted flat distribution (indicated by the histograms) are evident, contrary to expectations for S -wave $\pi^+\pi^-$ systems.

If the anomalous $\pi^+\pi^-\Upsilon(nS)$ events are due to an $Y(4260)$ -like particle in the b -quark sector, their peak mass and total width would not necessarily coincide with the corresponding $\Upsilon(5S)$ parameters. Belle investigated this with an energy scan around the $\Upsilon(5S)$ peak that measured the \sqrt{s} dependence of $\pi^+\pi^-\Upsilon(nS)$ production ($n = 1, 2$ & 3). The results of the scan, shown in Fig. 12, are that these event have a peaking structure and that the peak mass and full width, determined from a single BW fit to the three channels simultaneously are $M = 10889^{+6}_{-3}$ MeV and $\Gamma = 37^{+16}_{-10}$ MeV [43]. The measured peak mass value differs from the recent precise measurement by BaBar of $M_{\Upsilon(5S)} = 100876 \pm 2$ MeV – indicated by the vertical dashed line in Fig. 12 – by 2σ (systematic effects included) [44]. BaBar measures $\Gamma_{\Upsilon(5S)} = 43 \pm 4$ MeV, which is narrower than the PDG value and is not distinct from Belle's fitted width of the $\pi^+\pi^-\Upsilon(nS)$ peak.

The situation is summarized in Fig. 13, where Belle measurements of $R_{b\bar{b}}$, the total cross section for $e^+e^- \rightarrow b\bar{b}$ normalized to $\sigma_0(\mu^+\mu^-)$ is shown in Fig. 13a, the ratio of $\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))/\sigma(e^+e^- \rightarrow b\bar{b})$ is shown in Fig. 13b, and $R_{\pi^+\pi^-\Upsilon(nS)}$ in Fig. 13c. In the top figure the curve is the result of a fit with the $\Upsilon(5S)$ and $\Upsilon(6S)$

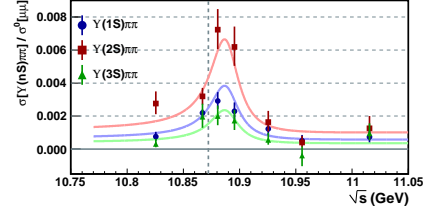


FIGURE 12. The \sqrt{s} dependence of $\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))$ for $n = 1$ (circles) $n = 2$ (squares) and $n = 3$ (triangles) from Belle. The curves are the result of the fit described in the text and the dashed vertical line indicates the $\Upsilon(5S)$ peak position.

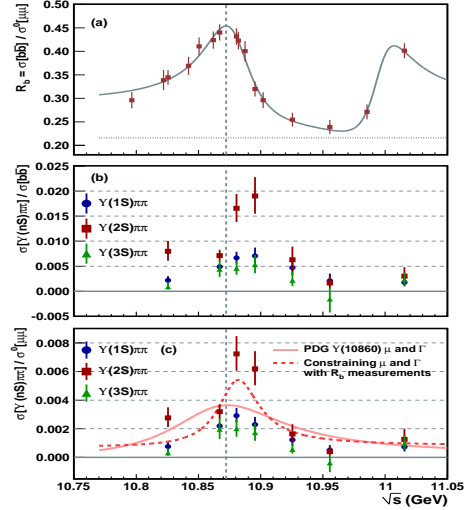


FIGURE 13. (a) R_b and (b) $\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))/\sigma(e^+e^- \rightarrow b\bar{b})$ (c) $R_{\pi^+\pi^-\Upsilon(nS)}$, the results of fits with resonance parameters from the R_b fit & the PDG fit are super imposed. The vertical dashed line indicates the \sqrt{s} value where $R_{b\bar{b}}$ is maximum. From ref. [43].

and an interfering non-resonant background (dashed horizontal line). The $\Upsilon(5S)$ parameters are allowed to float, the $\Upsilon(6S)$ parameters are taken fixed at the ref. [44] values. The dashed curve in the bottom figure is the fit to $\pi^+\pi^-\Upsilon(1S)$ data with mass and width constrained by the $R_{b\bar{b}}$ fit. When the $R_{b\bar{b}}$ constraint is relaxed, the χ^2 reduces by 8.71 with an increase of two degrees of freedom, indicating a $\sim 2.5\sigma$ preference for different parameters for the $b\bar{b}$ and $\pi^+\pi^-\Upsilon(nS)$ peaks. The vertical dashed line indicates the position of the maximum value of $R_{b\bar{b}}$. (The peak in $R_{b\bar{b}}$ is shifted from the fitted $\Upsilon(5S)$ resonance mass because of interference effects.)

Thus, as opposed to the $Y(4260)$ and the charmonium resonances where the anomalous $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ peak occurs at a dip in the $e^+e^- \rightarrow \text{hadrons}$ cross section and far from the masses of the known $1^{--}c\bar{c}$ resonances, in this case the data favor the interpretation that the peak

of the anomalous $\pi^+\pi^-\Upsilon(nS)$ signal is distinct from that of the $\Upsilon(5S)$ but only at the $\sim 2\sigma$ confidence level. Considerably more scanning data is needed to establish conclusively whether or not the $\Upsilon(5S)$ is the source of the anomalous events. Unfortunately, this will probably not be available at least until BelleII starts to operate in 2014 [45].

SUMMARY

Experimental progress on the XYZ particles is reviewed. Belle and BaBar both see significant signals for $X(3872) \rightarrow \gamma J/\psi$, but recent Belle results indicate that the $\mathcal{B}(X(3872) \rightarrow \gamma\psi')$ is not as large as reported earlier by BaBar. BaBar confirmed the Belle sighting of the $Y(3040) \rightarrow \omega J/\psi$ in B decays and Belle sees a similar peak in $\gamma\gamma \rightarrow \omega J/\psi$, suggesting that its J^{PC} quantum numbers are $0^{\pm+}$ or $2^{\pm+}$. BaBar confirms the existence of the subthreshold decay $X(3872) \rightarrow \omega J/\psi$ and their fit to the $\pi^+\pi^-\pi^0$ line shape mildly favors a 2^{-+} over a 1^{++} assignment for the $X(3872)$. CDF confirms their $Y(4140) \rightarrow \phi J/\psi$ signal with more data and see hints of another $\phi J/\psi$ mass peak around 4275 MeV. Belle sees a different narrow $\phi J/\psi$ mass peak in $\gamma\gamma$ collisions at 4350 MeV. BESIII confirms the BESII observations of the threshold $p\bar{p}$ mass peak in $J/\psi \rightarrow \gamma p\bar{p}$ decays and the $X(1835)\pi^+\pi^-\eta'$ in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decays. They also see two higher mass peaks in the $\pi^+\pi^-\eta'$ channel.

The Belle group's discovery of huge partial widths for " $\Upsilon(5S)'' \rightarrow \pi^+\pi^-\Upsilon(nS)$ ($n = 1$ & 2) is reviewed. Attempts to explain this as a rescattering effect run into problems with the experimentally measured $M(\pi^+\pi^-)$ and $\pi^+\pi^-$ helicity angle distributions. Belle measurements of the \sqrt{s} dependence of $\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))$ favor an alternative source for the anomalous events but with limited statistical confidence.

ACKNOWLEDGMENTS

I thank the QCHS-IX organizers for inviting me to give this talk. I also thank Yanping Huang, Fred Harris, Kai-Feng Chen and Guillermo Rios for their help in preparing this manuscript. This work is supported by the WCU program of the Ministry of Education Science and Technology National Research Foundation of Korea.

REFERENCES

1. S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 262001 (2003).
2. The inclusion of charge-conjugate modes is always implied. Also, when results are quoted, the reported statistical and systematic errors are added in quadrature.
3. D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **93**, 072001 (2004).
4. V.M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **93**, i62002 (2004).
5. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **71**, 071103 (2005).
6. A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **96**, 102001 (2006).
7. A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 132002 (2007).
8. K. Nakamura *et al.* (Particle Data Group) *J. Phys. G* **37**, 1 (2010).
9. S. Uehara *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **96**, 082003, (2006).
10. See, for example: F.E. Close and P.R. Page, *Phys. Lett.* **B578**, 316 (2004), M.B. Voloshin, *Phys. Lett.* **B579**, 316 (2004), S. Pakvasa and M. Suzuki, *Phys. Lett.* **B579**, 67 (2004), E.S. Swanson, *Phys. Lett.* **B588**, 189 (2004), N. Törnqvist, *Phys. Lett.* **B590**, 209 (2004) and E. Braaten, M. Kusunoki and S. Nussinov, *Phys. Rev. Lett.* **93**, 162001 (2004).
11. N.A. Törnqvist, *Z. Phys. C* **61**, 525, (1994).
12. T. Barnes, S. Godfrey and E.S. Swanson, *Phys. Rev. D* **72**, 054026, (2005).
13. Y. Jia, W.-L. Sang and J. Xu, arXiv:1007.4541.
14. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **102**, 132001 (2009).
15. V. Bhardwaj, talk at the the Quark Working Group 2010 meeting.
16. S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **94**, 182002 (2005).
17. T. Aushev *et al.* (Belle Collaboration), *Phys. Rev. D* **81**, 031103 (2010).
18. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **101**, 082001 (2008).
19. S. Uehara *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **104**, 092001 (2010).
20. E.S. Swanson, *Phys. Lett.* **B598**, 197 (2004).
21. K. Abe *et al.* (Belle Collaboration), hep-ex/0505037.
22. P. del Amo Sanchez *et al.* (BaBar Collaboration), *Phys. Rev. D* **82**, 011101 (2010).
23. Yu.S. Kalashnikova and A.V. Nefediev, arXiv:1008.2895.
24. A. Aaltonen *et al.* (CDF Collaboration), arXiv:0903.2229.
25. K. Yi, talk at the 2020 International Conference on High Energy Physics, Paris.
26. Perhaps a dynamical mechanism such as that explored in T. Branz, R. Molina and E. Oset, arXiv:1010.0587 is involved.
27. C.P. Shen *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **104**, 112004 (2010).
28. J.Z. Bai *et al.* (BESII Collaboration), *Phys. Rev. Lett.* **91**, 022001 (2003).
29. G.J. Ding and M.L. Yan, *Phys. Rev. C* **72**, 015208 (2005).
30. M. Ablikim *et al.* (BESII Collaboration), *Phys. Rev. Lett.* **95**, 262001 (2005).
31. M. Ablikim *et al.* (BESII Collaboration), *Chinese Phys. C* **34**, 421 (2010).
32. Y.-P. Huang, talk at the 2020 International Conference of High Energy Physics, Paris.

- 33. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **95**, 142001 (2005).
- 34. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **98**, 212001 (2007).
- 35. C.-Z. Yuan *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 182004 (2007).
- 36. X.-L. Wang *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 142002 (2007).
- 37. J.Z. Bai *et al.* (BES Collaboration), *Phys. Rev. Lett.* **88**, 101802 (2002).
- 38. X.-L. Wang *et al.*, *Phys. Lett.* **B640**, 182 (2007).
- 39. W.S. Hou, *Phys. Rev. D* **74**, 017504 (2006).
- 40. A. Sokolov *et al.* (Belle Collaboration), *Phys. Rev. D* **75**, 071103 (2007).
- 41. K.F. Chen *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 112001 (2008).
- 42. C. Meng and K.T. Chao, *Phys. Rev. D* **77**, 074004 (2008).
- 43. K.-F. Chen *et al.* (Belle Collaboration), arXiv:0808.2445.
- 44. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **102**, 012001 (2009).
- 45. T. Abe *et al.* (BelleII Collaboration), arXiv:1011.0352.